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# FLUID DYNAMICS TEST PRETEST REPORT MOL PROTUBERANCE HEATING WIND TUNNEL MODEL

## SEQUENCE NUMBER B334

Prepared under Contract Number F04695-67-C-0029
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EXHIBIT B, DATA ITEM NUMBER UT135

*By the MOL Subdivision*
*Missile and Space Systems Division*
*Douglas Aircraft Company*
*Huntington Beach, California*

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APPROVAL SHEET

FOR

PRETEST REPORT FOR MOL PROTUBERANCE HEATING

WIND TUNNEL MODEL

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ABSTRACT

This report outlines objectives and test requirements for wind tunnel testing of several protuberances unique to the MOL vehicle. An important feature of the testing program is the investigation of heating rates on protuberances wholly or partially submerged in a boundary layer. In order to achieve a thick boundary layer, the models are mounted on the floor of the tunnel. A thin, instrumented plate replaces the ordinary tunnel floor plates, in order to investigate the disturbances caused by the protuberances on the surrounding flow fields. A wake heating region of at least 35 inches will be available.

The protuberance models and the metric floor plate are constructed of thin nickel shells 1/16 inch thick. Heat transfer data will be collected by applying thin skin temperature response techniques. Half scale models of the VVSA, thrustor, ESE fairing, and VVSA-thrustor combination will be tested.

The models will be tested at Mach numbers of 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 and unit Reynolds number will be varied to the limits of the tunnel and structural limits of the models. The Mach number range corresponds to the period during the flight trajectory of most severe heating (60 to 160 seconds after liftoff). The Reynolds number range will be higher than flight Reynolds number because of tunnel limitations. With the exception of the asymmetric fairing, the models will be yawed up to 24°; flight pitch programs cannot be simulated except by varying Mach number and other tunnel parameters.

Data will be presented primarily in the form of ratios of heat transfer, $h/h_o$, and pressure, $P/P_o$, where subscript o refers to flat plate data. Plots will be made of boundary layer stream velocities, pressures, and Mach numbers. Temperature-time responses of the nickel shells and variations of $h/h_o$ along the tunnel centerline will be plotted. In addition, values of $h/h_o$ and $P/P_o$ for the floor instrumentation will be printed on plan schematics. Shadowgraphs will be taken of the protuberances and surrounding flow fields.

## DESCRIPTORS

Heat Transfer

Protuberance

MOL

Test

Wake

Wind Tunnel

## PREFACE

The MOL Protuberance Heating Test will be conducted in March 1968 for the Air Force Space Systems Division under Contract Number F04695-67-C-0029. An outline of the protuberance heating test was provided in Section 5 of SAFSL Exhibit 21010. A pretest report is required in the contract data requirements under line item 1AL1, data item No. UT-135.

The test will consist of three phases. Phase I will be a boundary layer survey of the tunnel floor, which is necessary to establish boundary layer thickness because the tunnel geometry for this test is unusual. Phase II will establish heating characteristics and pressure distributions on the floor with no protuberances. Phase III will consist of data collection on the protuberances, and the effect of the protuberances on the floor flow fields and heating rates.

Part of the test plan was previously presented in reference 1.

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## ILLUSTRATIONS

## 1.0 INTRODUCTION

### 1.1 MOL Protuberance Heating Test

The protuberance heating test will be conducted at the Douglas Aerophysics Laboratory, El Segundo, California in the Four-Foot Trisonic Wind Tunnel at supersonic Mach numbers with the transonic cart installed in the tunnel circuit. Wind tunnel models will be tested at Reynolds numbers as close to flight Reynolds numbers as can be attained.

### 1.2 Test Objectives

The primary objective of the test is to determine the aerodynamic heating rates and their distributions on the MOL protuberances, and on the skin and structures surrounding the protuberances. Other important objectives are to evaluate the effects of the protuberances on the surrounding viscous and inviscid flow fields, and compare to flat plate heating distributions and flow fields. There will be an opportunity to study wake heating effects for at least 35 inches behind the models. It is anticipated that a systematic approach to predicting inflight temperature histories on protuberances will develop from this test.

### 1.3 Implementation

Even though the MOL vehicle will attain Mach numbers as high as 11, the local Mach numbers around the protuberances will not exceed 5 during the time of peak heating, so a complete test program can be conducted at supersonic Mach numbers. The expected peak heating region is illustrated in figure 1.

The Douglas Aerophysics Laboratory Four-Foot Wind Tunnel is of the intermittent blowdown type. The operating envelope available for this test is shown on figure 2. This envelope is based on preliminary tests run to verify the feasibility of testing the large models with the unusual tunnel geometry necessary for this test (as explained subsequently).

The envelope is limited from running below Mach 2.5 because at that point the flow is blocked by the cooling shoe used to protect the model during start. The maximum total pressure and dynamic pressure are determined by the structural limitations of the model and usable, available run times. Resulting test conditions are included in table 1. Comparisons of test and flight Reynolds number and boundary layer thicknesses are also presented in figure 2.

### 1.4 Facility Scheduling

Tunnel modification was begun in January 1968. Because of heavy scheduling commitments, it will be necessary to conduct the boundary layer survey as a separate test using solid plates in the floor instead of the metric floor plate. An intervening test will be included between the boundary layer survey and primary test (Phase II).

Installation of the primary test will begin in early February, and will take several weeks. Testing is expected to begin on or near March 25.

## 2.0 MODEL DESCRIPTION

### 2.1 General Design Criteria

Heat transfer models built for applying skin temperature response techniques for gathering data are designed to meet several criteria, but of these probably the most important are the skin material and thickness. The material and thickness were selected to meet the following criteria:

$$B_i = \frac{hd}{K} \leq .0.1$$

If the Biot Modulus is small, the errors due to temperature gradients through the skin will be diminished.

$$F_o = \frac{\alpha t}{d^2} \geq 10$$

The Fourier Modulus is a measure of the degree heating effects have penetrated the skin, so in order for there to be good thermocouple response, it must be large.

The overall result from designing to the above criteria is to minimize errors due to temperature gradients through the skin and errors caused by surface conduction from one part of the model to another. A material thickness meeting the above criteria was too thin for some model parts, so the thermal design had to be compromised in order to meet the strength requirements. All model and floor plate skin thicknesses were set at 1/16 inch nominal, and the material chosen for all parts was nickel.

References 2, 3 and 4 expand on the subject of heat transfer model design.

## 2.2 Metric Floor Plate

### 2.2.1 General Configuration

The metric floor plate assembly is made up of three basic members. The center section consists of a 41 1/4 inch diameter turntable, which is necessary to yaw the smaller models.

Forward and aft skin sections extend the metric plate to 48 inches wide by 117 inches long. All members mount on insulative supports, which in turn mount to the tunnel stringers, the floor support structure.

### 2.2.2 Turntable

The turntable basically consists of four sections. The metric skin is heavily instrumented with pressure taps and thermocouples. Cutouts in the surface provide access to model mounting structures underneath. An insulative support mounts the skin to a base plate. The base plate provides support for the overall assembly, and provides attachments to tunnel support structure. The joint between the turntable and other skin members will be filled before each run to diminish the possibility of the joint causing a weak shock. The turntable will yaw through $\mp 24^{\circ}$. The clearance gap around the skin is sealed from the transonic cart plenum with an "O" ring. Thermocouple and pressure tap patterns are provided in figure 4 and table 3.

### 2.2.3 Forward and Aft Skin Sections

The forward and aft metric floor plate section mount to tunnel support structure through insulative supports. Floor insulative supports and the one for the turntable are cut away wherever they are not bearing or wherever strength is not needed in order to contact the skin as little as possible (according to reference 4, the best insulator on the underside of a thin skin model is dead air). The instrumentation layouts and general dimensions are shown on figures 5 and 6 and tables 4 and 5.

### 2.2.4 Convection Shield

A convection shield mounts between each stringer under the metric floor plate assembly. This eliminates convection under the plate and provides support for a network of tubes that will supply the liquid nitrogen for precooling. The shields are constructed of sheet aluminum.

### 2.3 Thrustor Assembly

The thrustor assembly to be tested is shown on figures 7 and 8. The model will mount on the turntable at tunnel station 155 as shown on the installation drawing, figure 3. The pressure taps are located on one side of the model, and thermocouples on the other. By taking advantage of the symmetry of the model, a complete analysis can be made of both windward or leeward sides by yawing in both plus and minus directions. The thrustor assembly will be yawed to $0^\circ$, $\pm 12^\circ$; and $\pm 24^\circ$.

The shell is reinforced by insulative bulkheads, one longitudinally positioned on the ℄ , and others transversely so that unsupported sections of the skin do not exceed a square of 3 inches on a side, in an attempt to hold deflection of the surface to 0.005 inch. The back mounts separately as do both contiguous and outboard nozzles. The module mounts on a base plate which mounts to the substructure under the turntable skin.

The thrustor and other models have a system of copper tubing routed to various parts of the interior. A standard pipe fitting is provided on the bottom of the base plate to accept the liquid nitrogen supply for precooling the model.

An instrumented wake length of 37 inches will be available for investigation.

### 2.4 VVSA - Thrustor Combination

The VVSA to be tested is shown on figures 9 and 10. The model will mount on the turntable at tunnel station 148 as shown on figure 3, and will be run only concurrently with the thrustor. As was the case with the thrustor, the VVSA is internally strengthened with insulative bulkheads, has thermocouples on one side, pressure taps on the other, and has a system of tubes for accepting liquid nitrogen. The model is mounted on a base plate. The VVSA - thrustor combination will be yawed to $0^\circ$, $\pm 12^\circ$, and $\pm 24^\circ$. A wake length of 37 inches will be available as with the thrustor alone.

### 2.5 Asymmetric Model

The asymmetric model is shown on figures 11 and 12. As was the case with the other two models, the interior is reinforced with bulkheads, the model mounts on a base plate, and is internally cooled. Flight trajectories for the MOL vehicle indicate it is not necessary to yaw this model. The tunnel on the side makes the model unsymmetrical, so pressure taps and thermocouples are equally distributed. The instrumentation is concentrated near the tunnel because the other surfaces are similar to model geometries of several previous wind tunnel tests.

The model leading edge will mount at tunnel station 125, and a wake heating length of 35 inches will be available.

## 3.0 FACILITY INSTALLATION

### 3.1 The Douglas Aerophysics Laboratory Four-Foot Trisonic Wind Tunnel

The Douglas Aerophysics Laboratory Four-Foot Trisonic Wind Tunnel is well suited for the MOL protuberance test for two reasons. First, it is an intermittent blowdown tunnel. The tunnel can be started and brought up to steady-state conditions abruptly, and the shoe will protect the model during this brief period of unstable flow. Thus the temperature shock is essentially a step input, and can be treated that way in data reduction without appreciable error. By contrast, if this model were floor mounted in a continuous tunnel, the temperature step input would be accomplished by increasing the tunnel freestream total temperature. Ordinarily, this means the variation of total temperature must be considered in data reduction to avoid significant errors.

The second consideration that makes the Four-Foot Tunnel attractive for this test is the flexibility in model design and the thick boundary layer made possible by the transonic cart.

### 3.2 The Four-Foot Wind Tunnel Transonic Cart

The transonic cart is a removable section of the tunnel that ordinarily performs several functions:

a. The test section is extended from 5 to 12 feet long.

b. Walls are covered with perforated steel plates to help diminish the wall boundary layer thickness and weaken shocks impinging upon them.

c. A plenum surrounding the test section is connected upstream and downstream to the main air flow through large, remotely controlled butterfly valves. These valves control the amount of air bypassing the test section, and are thus used to vary the Mach number during transonic operation. There are approximately 14 inches between the perforated plates and the plenum outerwall.

For this project, the transonic cart will be retained in the tunnel circuit during a supersonic test for several reasons:

1. The extra length of test section is needed to thicken the boundary layer.

2. The perforated plates may be replaced with an unperforated plate, the metric floor plate, facilitating mounting the models. (It is not possible to mount models this way in the supersonic section without damaging either the sidewalls or the flexible nozzle). The support structure for the perforated plates, the tunnel stringers, are also used for mounting the model.

3. The plenum provides a means of access underneath the floor plate and models. The plenum can also be used to mount auxiliary equipment, such as the shadowgraph system and the LN2 supply, and it provides a space for routing model instrumentation leads.

### 3.3 Modifications to the Transonic Cart

A convection shield (already mentioned) consisting of sections of sheet aluminum will be mounted between the stringers, and a few inches below the metric floor plate.

The tunnel stringers will have to be shortened near tunnel station 160 in order to provide clearance for the turntable.

The perforated plates will be replaced with solid aluminum plates to stop air from entering the plenum and recirculating, to improve the flow, and to stop air circulation in the plenum from affecting thermocouple response by introducing convection losses.

### 3.4 Hydraulic Shoe

In order to protect the model during start, a hydraulically actuated shoe had to be designed. This shoe differs from standard tunnel equipment in that a piston with a 48 inch stroke was necessary (floor to ceiling).

Ordinary shoes only extend to tunnel centerline. The large size dictated a stronger shaft than is ordinarily necessary. In order to be most effective, the shoe was moved six inches forward of its usual position.

### 3.5 Liquid Nitrogen System

In order to achieve a good temperature rise during a blow, it will be necessary to chill the models and floor plate with liquid nitrogen, since for most Mach numbers the stagnation temperature is close to ambient. It is anticipated that the LN2 will bring the initial temperatures down to -75°F.

## 4.0 INSTRUMENTATION

### 4.1 Pressure Taps

Pressure taps are 1/16 x 0.010 inch wall stainless tubing. The distribution of pressure taps is as follows (also refer to figures 5-13):

| | |
|---|---|
| Forward Floor Skin | 6 |
| Turntable | 77 |
| Aft Floor Skin | 13 |
| Asymmetric Fairing | 24 |
| Thrustor Assembly | 31 |
| VVSA | 37 |

The pressures will probably be connected to two banks of scannivalves (model D), each having five modules, with one port of each module reading a reference pressure. However, it is possible that tunnel personnel will select another type of pressure scanner. The longest lag time (for a tube 102 inches long) will be about 2 1/2 seconds. Pressures on the metric floor plate will be close to free-stream static. Maximum model pressures will approach 20 psia (ramp on the thrustor, leading edge of the VVSA, tunnel on asymmetric model).

### 4.2 Thermocouples

Copper-constantan thermocouples (0.012 inch diameter) are welded to the inside of the skin at the locations indicated in the figures. The small gage wire is necessary to minimize errors resulting from heat conduction along the wire.

All of the wire used in the model has been certified by Revere Corporation to have the following outputs:

| Temperature | Emf |
|---|---|
| $-100^{\circ}F$ | -2.575 mv |
| $-300^{\circ}F$ | 6.637 mv |

Certificates are on file in company receiving records. Each wire and pair are insulated with nylon. Thermocouple distribution among the model parts is as follows:

| | |
|---|---|
| Forward Floor Skin | 27 |
| Turntable | 152 |
| Aft Floor Skin | 24 |
| Asymmetric Fairing | 58 |
| Thrustor Assembly | 29 |
| VVSA | 34 |

Thermocouples are connected to a Pace Engineering Company reference junction operating at $150^{\circ} \pm 0.2^{\circ}F$.

## 4.3 Nickel

The nickel used for the model shells was electroplated. The nickel used for the metric floor plate was sheet stock (half hard).

Both types of nickel are estimated by the manufacturers to contain less than 1% impurities. However, thermodynamic properties will be measured at room temperature as a check. Standard tables providing the variation of thermal properties with temperature will ultimately be used in data reduction.

## 5.0 DATA REQUIRED

Data collected will consist of tabulated data, plotted data, and photographic data (shadowgraphs and installation photographs). The requirements for each phase of testing will vary. See the appendix for definitions of symbols used subsequently.

### 5.1 Tabulated Data

#### 5.1.1 Tunnel Freestream Parameters

Tunnel freestream parameters will be provided for all phases of testing:

$T_{T_\infty}$, $T_\infty$, $P_{T_\infty}$, $P_\infty$, $\rho_\infty$, $\rho_{T_\infty}$, $V_\infty$, $M_\infty$, $q_\infty$, Re/in

#### 5.1.2 Boundary Layer Survey, Phase I

During the boundary layer survey, the parameters under 5.1.1 will be listed along with $\delta$.

#### 5.1.3 Flat Plate Reference Runs, Phase II

During this phase of testing, parameters under 5.1.1 will be provided along with the following:

T vs t (for a few selected thermocouples), $h_o$, $P_o$,

$R_{e_{x=o}}$

$h_o$ and $P_o$ will be provided for each thermocouple and orifice, respectively.

#### 5.1.4 Protuberance Testing, Phase III

During this phase of testing, parameters under 5.1.1 will be provided along with the following:

h, $h/h_o$, CP, $P/P_o$, $\beta$

These parameters (except $\beta$) will be provided for each thermocouple and orifice, respectively.

## 5.2 Plotted Data

### 5.2.1 Boundary Layer Survey, Phase I

During this phase of testing the following shall be plotted

$$N = Z/\delta \quad \text{vs} \quad \frac{M}{M_\infty}, \quad \frac{P_{Tj}}{P_{T_\infty}}, \quad \frac{u_j}{U_\infty}$$

for each boundary layer rake pressure tap.

### 5.2.2 Flat Plate Reference Runs, Phase II

During this phase of testing the following shall be plotted:

T vs t (for a few selected thermocouples).

In addition, $h_o$ and $P_o$ will be printed out on a plan schematic of the floor at each thermocouple and pressure tap, respectively.

### 5.2.3 Protuberance Testing, Phase III

During this phase of testing the following shall be plotted:

T vs t (for a few selected thermocouples)

X vs $h/h_o$

In addition, $h/h_o$ and $P/P_o$ will be printed out on a plan schematic,

The X plots will be on tunnel centerline only at zero yaw. These plots will not extend over the model.

## 5.3 Photographic Data

Installation photographs will be taken when requested by the test director. Shadowgraphs will be taken for each model configuration and Mach number. The field of view and the spark source locations are provided on figure 3.

## REFERENCES


1. Test Control Dwg. 1T22216, Model, Pretuberance - Development Test - TCD, dated 12 July 1967.

2. Douglas Report DAC-59809, The Douglas Aerophysics Laboratory Four-Foot Trisonic Wind Tunnel, dated October 1967.

3. Naismith, A., Measurement of Aerodynamic Heat Transfer in Intermittent Wind Tunnels, Royal Aircraft Establishment Technical Report CP-780, dated January 1964.

4. McMahan, H. M., "An Experimental Study of the Effect of Mass Injection at the Stagnation Point of a Blunt Body," GALCIT Hypersonic Research Project, Memorandum No. 42, dated 1 May 1950.

5. Douglas Report DAC-59801, Improved Turbulent Skin Friction Coefficient Predictions Utilizing the Spalding-Chi Method, dated November 1966.

Table 1 Preliminary Run Schedule (Sheet 1 of 4)

| Configuration | Run No. | $M_\infty$ | $P_{T_\infty}$ (psia) | $T_{T_\infty}$ (°F) | Re/in $10^{-6}$ | β (Deg) | Data Take T | Data Take P | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| Rake at STA 23 | 1 | 2.5 | 27 | 70 | .50 | --- | yes | yes | Start Phase I |
| | 2 | 3.0 | 35 | | .50 | | | | |
| | 3 | ↓ | 40 | | .55 | | | | |
| | 4 | 3.5 | 40 | | .44 | | | | |
| | 5 | ↓ | 65 | | .71 | | | | |
| | 6 | 4.0 | 95 | | .90 | | | | |
| | 7 | ↓ | ↓ | ↓ | | | | | Repeat of No. 6 |
| | 8 | 4.5 | 80 | 150 | | | | | |
| | 9 | ↓ | 110 | ↓ | | | | | |
| | 10 | 5.0 | 110 | 150 | ↓ | | | | |
| Rake at STA 188 | 11 | 2.5 | 27 | 70 | .50 | | | | |
| | 12 | 4.0 | 95 | ↓ | .90 | | | | |
| | 13 | 5.0 | 110 | 150 | .90 | | | | |
| $M_1$ | 14 | 2.5 | 27 | 70 | .50 | | | | Start Phase II |
| | 15 | ↓ | ↓ | | ↓ | | | | Repeat No. 14 |
| | 16 | 3.0 | 35 | | .50 | | | | |
| | 17 | ↓ | 40 | | .55 | | | | |
| | 18 | 3.5 | 40 | | .44 | | | | |
| | 19 | | 65 | | .71 | | | | |
| | 20 | ↓ | ↓ | | ↓ | | | | Repeat No. 19 |
| | 21 | 4.0 | 95 | ↓ | .90 | | | | |
| | 22 | 4.5 | 80 | 150 | | | | | |
| | 23 | 4.5 | 110 | | | | | | |
| | 24 | ↓ | ↓ | ↓ | | | | | Repeat No. 23 |
| | 25 | 5.0 | 110 | 150 | | | | | |
| | 26 | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | Repeat No. 25 |

Table 1 Preliminary Run Schedule (Sheet 2 of 4)

| Configuration $M_1$ $M_2$ | Run No. | $M_\infty$ | $P_{T_\infty}$ (psia) | β (Deg) | Data Taken T | Data Taken P | *Light Source | Remarks |
|---|---|---|---|---|---|---|---|---|
| | 27 | 2.5 | 27 | 0 | yes | yes | 125 | Asymmetric Model |
| | 28 | 3.0 | 35 | ↓ | ↓ | ↓ | ↓ | |
| | 29 | 3.5 | 40 | | | | | |
| | 30 | 4.0 | 95 | | | | | |
| | 31 | 4.5 | 110 | | | | | |
| | 32 | 5.0 | 110 | | | | | |
| | 33 | 5.0 | ↓ | | | no | | Pickup rest T.C. data |
| | 34 | 4.5 | 110 | | | ↓ | | |
| | 35 | 4.0 | 95 | | | | | |
| | 36 | 3.5 | 40 | | | | | |
| | 37 | 3.0 | 35 | | | | | |
| | 38 | 2.5 | 27 | | | | | |
| $M_1$ $M_3$ | 39 | 2.5 | 27 | | Yes | Yes | 155 | Thrustor |
| | 40 | 3.0 | 45 | | ↓ | ↓ | ↓ | |
| | 41 | 3.5 | 65 | | | | | |
| | 42 | ↓ | ↓ | | | | | Repeat No. 41 |
| | 43 | | | +12 | | | | |
| | 44 | | | -12 | | | | |
| | 45 | 4.0 | 95 | 0 | | | | |
| | 46 | ↓ | ↓ | +12 | | | | |
| | 47 | | | -12 | | | | |
| | 48 | 4.5 | 80 | 0 | | | | |
| | 49 | ↓ | ↓ | +24 | | | | |
| | 50 | | | -24 | | | | |
| | 51 | | | ↓ | | | | Repeat at No. 50 |
| | 52 | 5.0 | 110 | 0 | | | | |

* Shadowgraph light source tunnel station.

Table 1 Preliminary Run Schedule (Sheet 3 of 4)

| Configuration $M_1$ $M_4$ | Run No. | $M_\infty$ | $P_{T_\infty}$ (psia) | β (Deg) | Data Taken T | Data Taken P | Light Source | Remarks |
|---|---|---|---|---|---|---|---|---|
| | 53 | 2.5 | 27 | 0 | yes | yes | 147.8 | VVSA + Thrustor |
| | 54 | 3.0 | 40 | ↓ | ↓ | ↓ | ↓ | |
| | 55 | 3.5 | 65 | +12 | | | | |
| | 56 | ↓ | ↓ | -12 | | | | |
| | 57 | | | ↓ | | | | Repeat No. 56 |
| | 58 | 4.0 | 110 | 0 | | | | |
| | 59 | ↓ | ↓ | +12 | | | | |
| | 60 | | | ↓ | | | | Repeat No. 59 |
| | 61 | | | -12 | | | | |
| | 62 | 4.5 | 80 | 0 | | | | |
| | 63 | ↓ | ↓ | +24 | | | | |
| | 64 | | | ↓ | | | | Repeat No. 63 |
| | 65 | | | -24 | | | | |
| | 69 | | | ↓ | yes | no | | Pickup rest of T.C. data. |
| | 70 | 2.5 | 27 | 0 | ↓ | ↓ | | |
| | 71 | 3.0 | 40 | 0 | | | | |
| | 72 | 3.5 | 65 | 0 | | | | |
| | 73 | ↓ | ↓ | +12 | | | | |
| | 74 | | | -12 | | | | |
| | 75 | 4.0 | 110 | 0 | | | | |
| | 76 | ↓ | ↓ | +12 | | | | |
| | 77 | | | -12 | | | | |
| | 78 | 4.5 | 80 | 0 | | | | |
| | 79 | ↓ | ↓ | +24 | | | | |
| | 80 | | | -24 | | | | |

Table 1 Preliminary Run Schedule (Sheet 4 of 4)

| Configuration | Run No. | $M_\infty$ | $P_{T\infty}$ (psia) | $\beta$ (Deg) | Data Taken T | Data Taken P | Light Source | Remarks |
|---|---|---|---|---|---|---|---|---|
| $M_1$ $M_4$ | 66 | 5.0 | 110 | 0 | Yes | Yes | 147.8 | |
| | 67 | | | +24 | | | | |
| | 68 | | | -24 | | | | |
| | 81 | | | 0 | | No | | |
| | 82 | | | +24 | | | | |
| | 83 | | | -24 | | | | Last Run |
| | | | | | | | | |

TABLE 2

MODEL CONFIGURATION SYMBOLS

| SYMBOL | DESCRIPTION |
|---|---|
| $M_1$ | Metric Floor Plate |
| $M_2$ | Asymmetric Model |
| $M_3$ | Thrustor Assembly |
| $M_4$ | VVSA - Thrustor Assembly Combination |

Table 3 Instrumentation Locations for Turntable Skin (Sheet 1 of 3)

## THERMOCOUPLES

| T.C. No | X | Y | T.C. No | X | Y | T.C. No | X | Y |
|---|---|---|---|---|---|---|---|---|
| 1 | -11.000 | +16.000 | 19 | -5.000 | +12.000 | 37 | +3.000 | +10.000 |
| 2 | -1.000 | | 20 | -3.000 | | 38 | +5.000 | |
| 3 | +1.000 | | 21 | -1.000 | | 39 | +9.000 | |
| 4 | +3.000 | | 22 | +1.000 | | 40 | +11.000 | |
| 5 | -12.500 | +14.000 | 23 | +3.000 | | 41 | +15.000 | |
| 6 | -11.000 | | 24 | +5.000 | | 42 | -17.000 | +8.000 |
| 7 | -9.000 | | 25 | +7.000 | | 43 | -15.000 | |
| 8 | -7.000 | | 26 | +9.000 | | 44 | -11.000 | |
| 9 | -5.000 | | 27 | +11.000 | | 45 | -9.000 | |
| 10 | -1.000 | | 28 | +13.000 | | 46 | -7.000 | |
| 11 | +1.000 | | 29 | -17.000 | +10.000 | 47 | -3.000 | |
| 12 | +9.000 | | 30 | -15.000 | | 48 | -1.000 | |
| 13 | +11.000 | | 31 | -11.000 | | 49 | +1.000 | |
| 14 | -15.000 | +11.500 | 32 | -7.000 | +11.000 | 50 | +3.000 | |
| 15 | -13.000 | +12.000 | 33 | -5.000 | +10.000 | 51 | +5.000 | |
| 16 | -11.000 | | 34 | -3.000 | | 52 | +7.000 | |
| 17 | -9.000 | | 35 | -1.000 | | 53 | +9.000 | |
| 18 | -7.000 | | 36 | +1.000 | | 54 | +13.000 | |

Refer to figure 4 for schematic

Table 3 Instrumentation Locations for Turntable Skin (Sheet 2 of 3)

## THERMOCOUPLES

| T.C. No | X | Y | T.C. No | X | Y | T.C. No | X | Y |
|---|---|---|---|---|---|---|---|---|
| 55 | -9.000 | +6.000 | 89 | -7.000 | +2.000 | 123 | -3.000 | -10.000 |
| 56 | -7.000 | | 90 | -5.000 | | 124 | -1.000 | |
| 57 | -5.000 | | 91 | -3.000 | | 125 | +1.000 | |
| 58 | -3.000 | | 92 | -1.000 | | 126 | -15.000 | -11.500 |
| 59 | -1.000 | | 93 | +1.000 | | 127 | -13.000 | -11.000 |
| 60 | +1.000 | | 94 | +11.000 | | 128 | -11.000 | -12.000 |
| 61 | +3.000 | | 95 | +13.000 | | 129 | -9.000 | |
| 62 | +5.000 | | 96 | +15.000 | | 130 | -7.000 | -11.000 |
| 63 | +7.000 | | 97 | +19.000 | | 131 | -7.000 | -12.000 |
| 64 | +9.000 | | 98 | -1.000 | +1.000 | 132 | -3.000 | |
| 65 | +13.000 | | 99 | -13.000 | 0 | 133 | -1.000 | |
| 66 | +15.000 | | 100 | -11.000 | | 134 | +1.000 | |
| 67 | -11.000 | +4.000 | 101 | -9.000 | | 135 | +3.000 | |
| 68 | -9.000 | | 102 | -7.000 | | 136 | -12.500 | -14.000 |
| 69 | -7.000 | | 103 | -5.000 | | 137 | -11.000 | |
| 70 | -5.000 | | 104 | -3.000 | | 138 | -9.000 | |
| 71 | -3.000 | | 105 | -1.000 | | 139 | -7.000 | |
| 72 | -1.000 | | 106 | +11.000 | | 140 | -3.000 | |
| 73 | +1.000 | | 107 | +13.000 | | 141 | -1.000 | |
| 74 | +3.000 | | 108 | +15.000 | | 142 | +1.000 | |
| 75 | +5.000 | | 109 | +17.000 | | 143 | +5.000 | |
| 76 | +7.000 | +4.500 | 110 | +19.000 | | 144 | -12.500 | -15.500 |
| 77 | +9.000 | +4.000 | 111 | -17.000 | -8.000 | 145 | -11.000 | -16.000 |
| 78 | +11.000 | | 112 | -15.000 | | 146 | -9.000 | |
| 79 | +13.000 | +4.500 | 113 | -13.000 | | 147 | -7.000 | -15.250 |
| 80 | +17.000 | +4.000 | 114 | -11.000 | | 148 | -5.000 | -16.000 |
| 81 | -8.000 | +3.000 | 115 | -3.000 | | 149 | -1.000 | |
| 82 | -4.000 | | 116 | -1.000 | | 150 | +1.000 | |
| 83 | -2.000 | | 117 | -5.000 | | 151 | +3.000 | |
| 84 | +1.000 | | 118 | +13.000 | | 152 | +5.000 | |
| 85 | -13.000 | +2.000 | 119 | -17.000 | -10.000 | | | |
| 86 | -11.000 | | 120 | -15.000 | | | | |
| 87 | -9.000 | | 121 | -11.000 | | | | |
| 88 | -8.000 | +1.500 | 122 | -9.000 | | | | |

Table 3 Instrumentation Locations for Turntable Skin (Sheet 3 of 3)

## PRESSURE TAPS

| P.T. No. | X | Y | P.T. No | X | Y | P.T. No. | X | Y |
|---|---|---|---|---|---|---|---|---|
| 1 | -3.000 | +14.000 | 28 | -3.000 | -4.000 | 55 | -5.000 | -8.000 |
| 2 | +3.000 | | 29 | -1.000 | | 56 | +1.000 | |
| 3 | -9.000 | +10.000 | 30 | +1.000 | | 57 | +3.000 | |
| 4 | -13.000 | +8.000 | 31 | +3.000 | | 58 | +7.000 | |
| 5 | -5.000 | | 32 | +5.000 | | 59 | +9.000 | |
| 6 | -11.000 | | 33 | +7.000 | -4.500 | 60 | +11.000 | |
| 7 | +17.000 | | 34 | +9.000 | -4.000 | 61 | +17.000 | |
| 8 | -19.000 | +6.000 | 35 | +11.000 | | 62 | -5.000 | -10.000 |
| 9 | -1.000 | -1.000 | 36 | +13.000 | -4.500 | 63 | +3.000 | |
| 10 | -13.000 | -2.000 | 37 | +17.000 | -4.000 | 64 | +5.000 | |
| 11 | -11.000 | | 38 | -13.000 | -6.000 | 65 | +9.000 | |
| 12 | -9.000 | | 39 | -11.000 | | 66 | +11.000 | |
| 13 | -8.000 | -1.500 | 40 | -9.000 | | 67 | +15.000 | |
| 14 | -7.000 | -2.000 | 41 | -7.000 | | 68 | -5.000 | -12.000 |
| 15 | -5.000 | | 42 | -5.000 | | 69 | +5.000 | |
| 16 | -3.000 | | 43 | -3.000 | | 70 | +7.000 | -11.000 |
| 17 | -1.000 | | 44 | -1.000 | | 71 | +9.000 | -12.000 |
| 18 | 0 | | 45 | +1.000 | -5.750 | 72 | +11.000 | |
| 19 | +11.000 | | 46 | +3.000 | -6.000 | 73 | +13.000 | |
| 20 | +13.000 | | 47 | +5.000 | | 74 | +3.000 | -14.000 |
| 21 | +15.000 | | 48 | +7.000 | | 75 | +7.000 | |
| 22 | +19.000 | | 49 | +9.000 | | 76 | +9.000 | |
| 23 | -13.000 | -4.500 | 50 | +11.000 | | 77 | -3.000 | -16.000 |
| 24 | -11.000 | -4.000 | 51 | +13.000 | | 78 | | |
| 25 | -9.000 | | 52 | +15.000 | | 79 | | |
| 26 | -7.000 | -4.500 | 53 | -9.000 | -8.000 | 80 | | |
| 27 | -5.000 | -4.000 | 54 | -7.000 | | 81 | | |

TABLE 4

INSTRUMENTATION LOCATIONS FOR FORWARD FLOOR SKIN

THERMOCOUPLES

| T. C. No. | X | Y | T. C. No. | X | Y |
|---|---|---|---|---|---|
| 1 | 15.000 | +18.000 | 15 | 21.750 | +6.000 |
| 2 | 23.000 | +14.000 | 16 | 35.000 | +2.000 |
| 3 | 21.000 | | 17 | 33.000 | |
| 4 | 19.000 | | 18 | 31.000 | |
| 5 | 31.000 | + 8.000 | 19 | 29.000 | |
| 6 | 29.000 | | 20 | 27.000 | |
| 7 | 27.000 | | 21 | 37.000 | 0.000 |
| 8 | 25.000 | | 22 | 35.000 | |
| 9 | 23.000 | | 23 | 33.000 | |
| 10 | 21.250 | | 24 | 31.500 | |
| 11 | 29.000 | + 6.000 | 25 | 33.000 | -2.000 |
| 12 | 27.000 | | 26 | 31.000 | |
| 13 | 25.000 | | 27 | 29.000 | |
| 14 | 23.000 | | | | |

PRESSURE TAPS

| P. T. No. | X | Y | P. T. No. | X | Y |
|---|---|---|---|---|---|
| 1 | 33.000 | +6.000 | 4 | 27.000 | -2.000 |
| 2 | 31.000 | | 5 | 23.000 | |
| 3 | 35.000 | -2.000 | 6 | 15.00 | -18.000 |

Refer to figure 5 for schematic

## TABLE 5

## INSTRUMENTATION LOCATIONS FOR AFT FLOOR SKIN

### THERMOCOUPLES

| T. C. No. | X | Y | T. C. No. | X | Y |
|---|---|---|---|---|---|
| 1 | 28.000 | +14.000 | 13 | 44.000 | +2.000 |
| 2 | 36.000 | | 14 | 24.000 | 0.000 |
| 3 | 44.000 | | 15 | 26.000 | |
| 4 | 21.000 | +6.000 | 16 | 28.000 | |
| 5 | 28.000 | | 17 | 30.000 | |
| 6 | 36.000 | | 18 | 32.000 | |
| 7 | 44.000 | | 19 | 34.000 | |
| 8 | 24.000 | +2.000 | 20 | 36.000 | |
| 9 | 28.000 | | 21 | 38.000 | |
| 10 | 32.000 | | 22 | 40.000 | |
| 11 | 36.000 | | 23 | 42.000 | |
| 12 | 40.000 | | 24 | 44.000 | |

### PRESSURE TAPS

| P. T. No. | X | Y | P. T. No. | X | Y |
|---|---|---|---|---|---|
| 1 | 24.000 | -2.000 | 8 | 28.000 | -6.000 |
| 2 | 28.000 | | 9 | 36.000 | |
| 3 | 32.000 | | 10 | 44.000 | |
| 4 | 36.000 | | 11 | 28.000 | -14.000 |
| 5 | 40.000 | | 12 | 36.000 | |
| 6 | 44.000 | | 13 | 44.000 | |
| 7 | 21.000 | -6.000 | | | |

See figure 6 for schematic

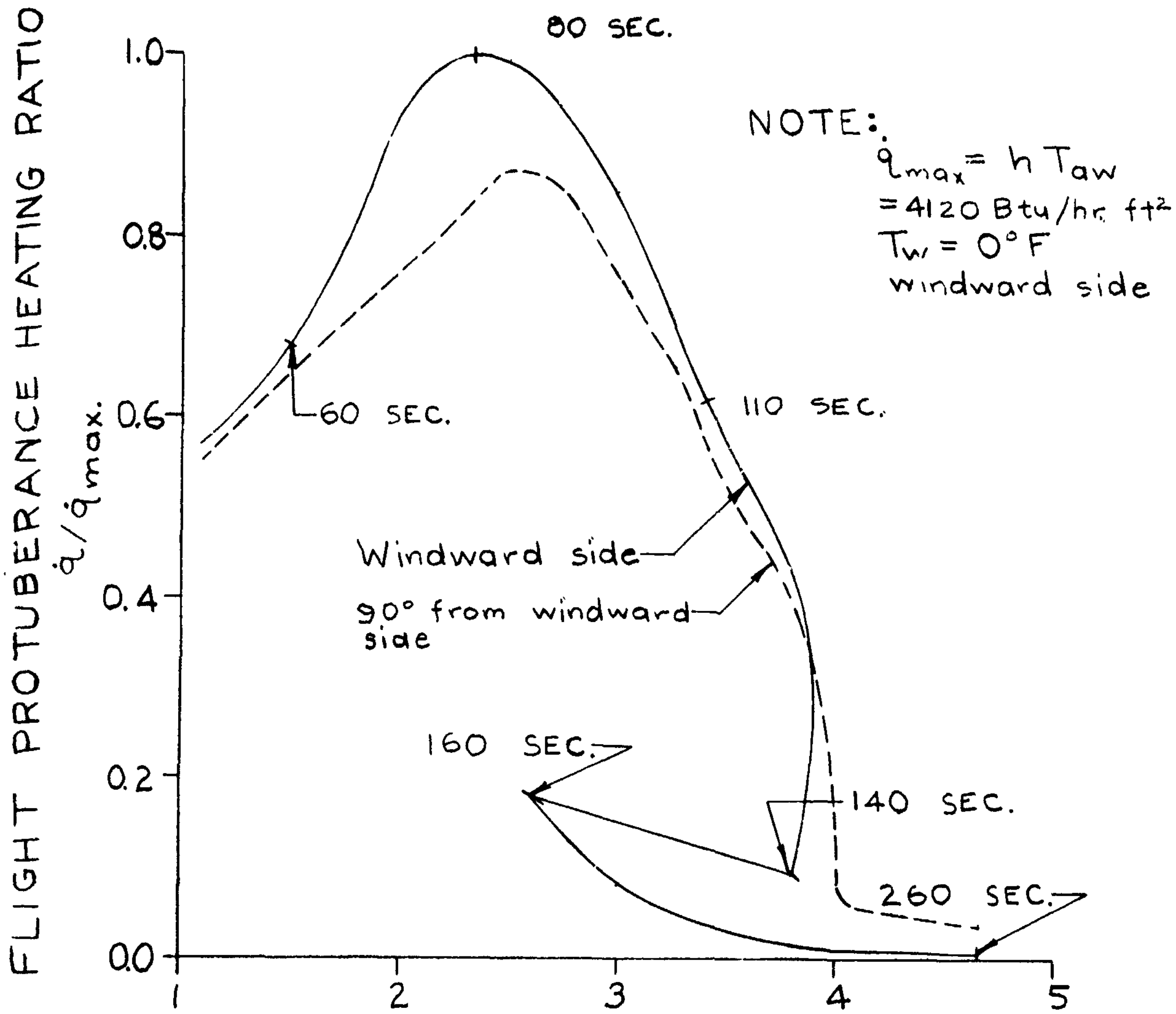



FIGURE 1. MOL Flight Protuberance Heating History

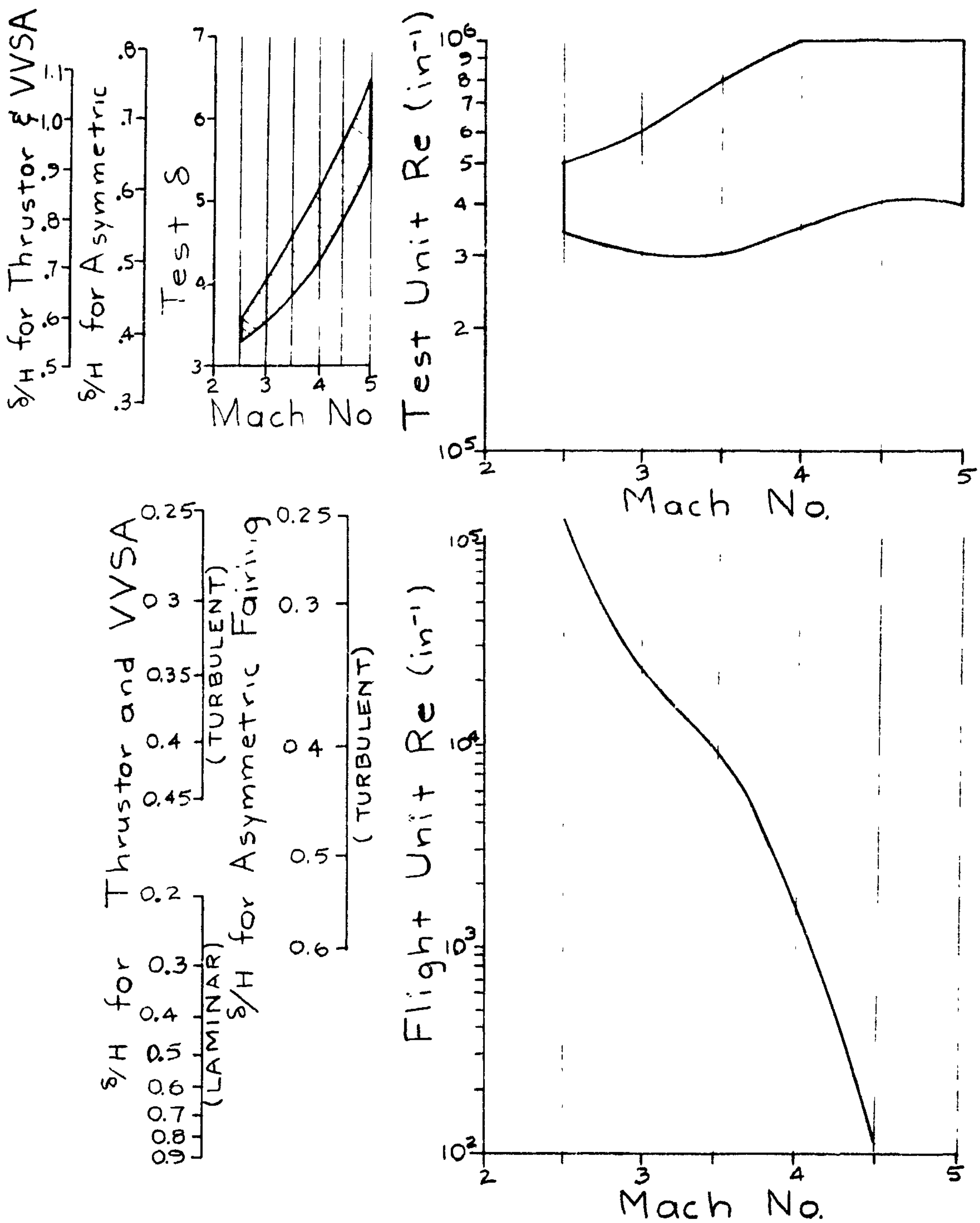



FIGURE 2. Comparison of Flight and Test Unit Reynold's Number and Boundary Layer Thickness

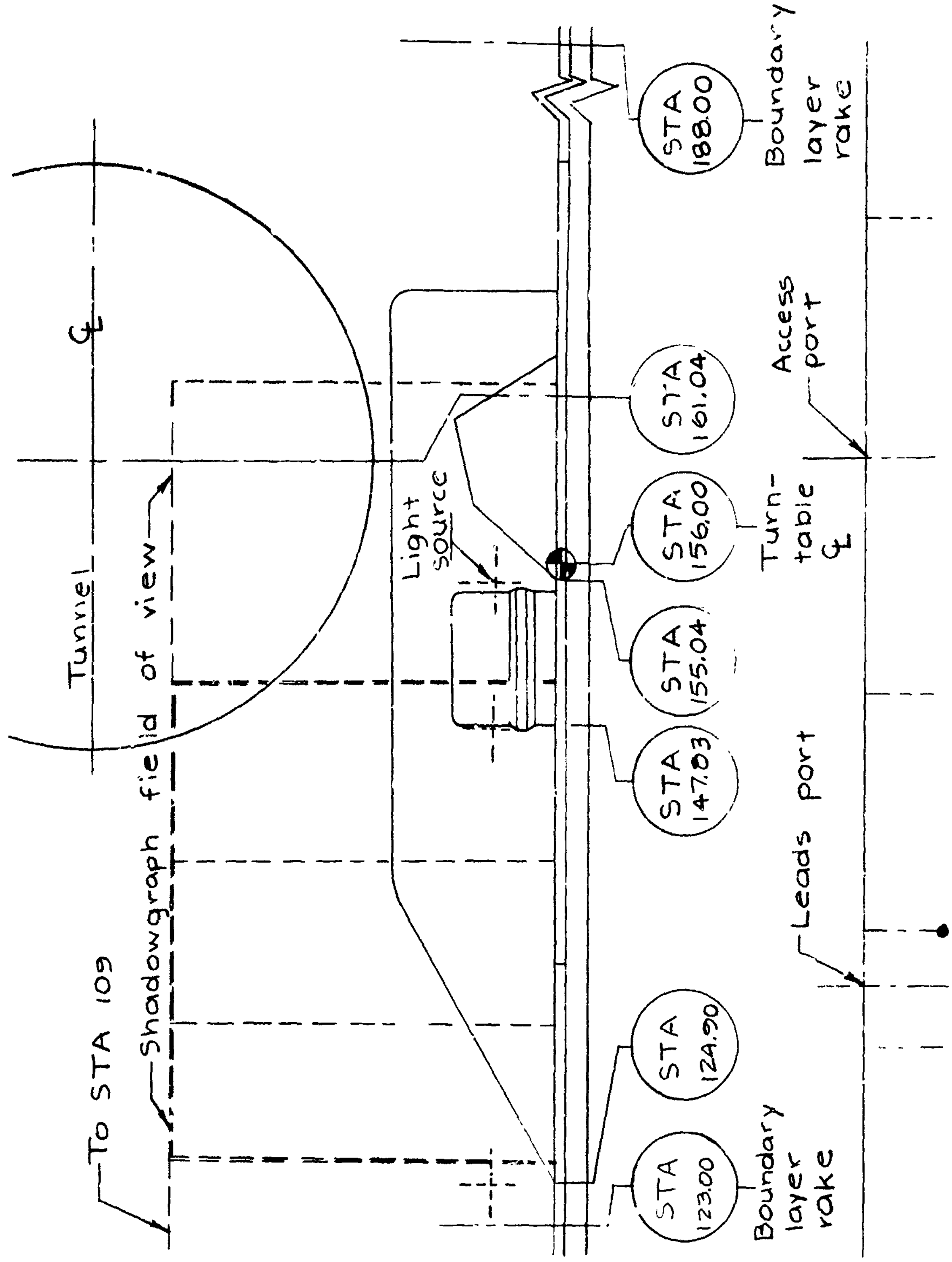
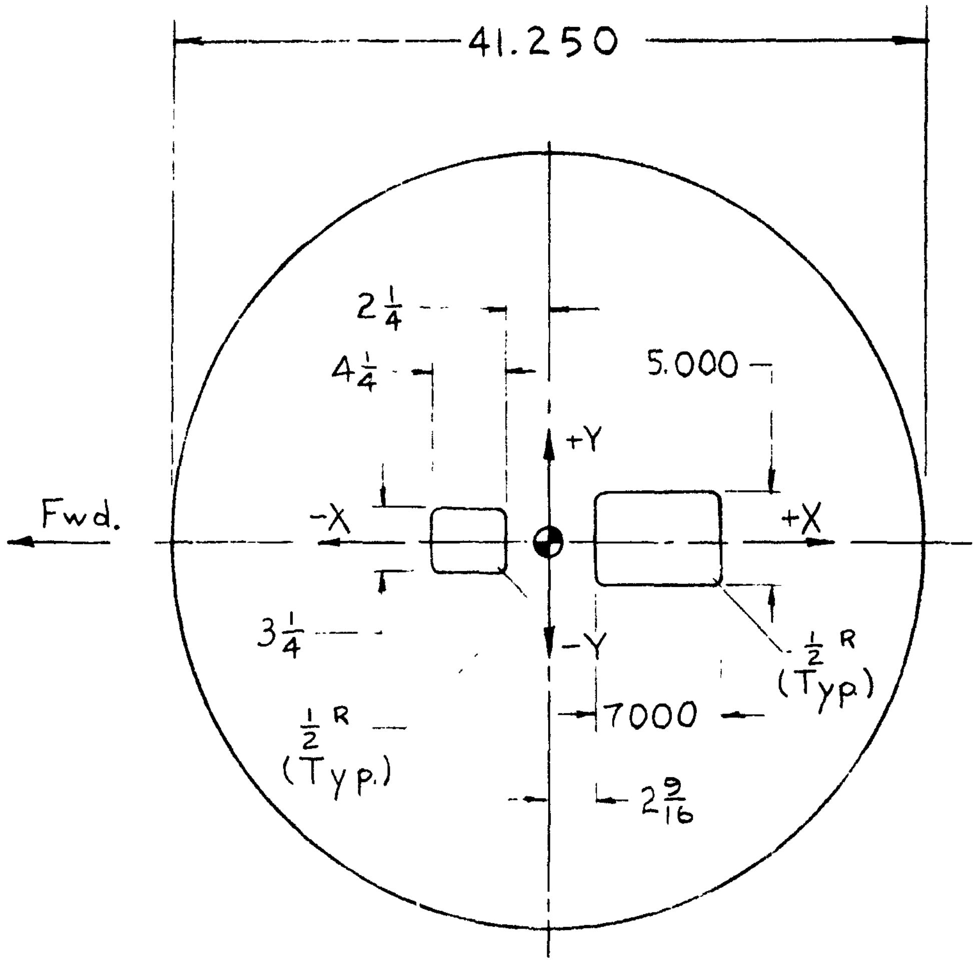
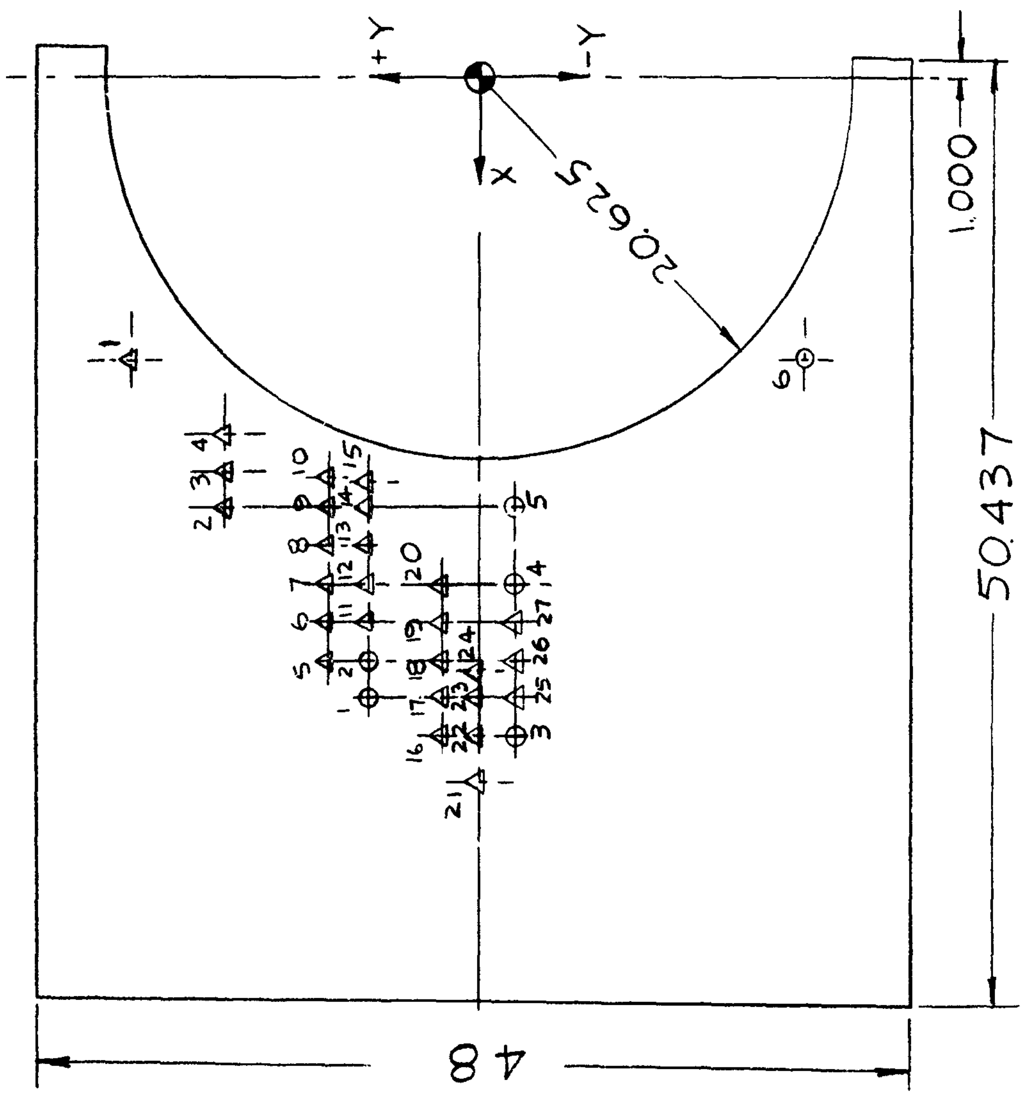



FIGURE 3. Schematic of Model Installations in Douglas Aerophysics Laboratory Four-Foot Trisonic Wind Tunnel



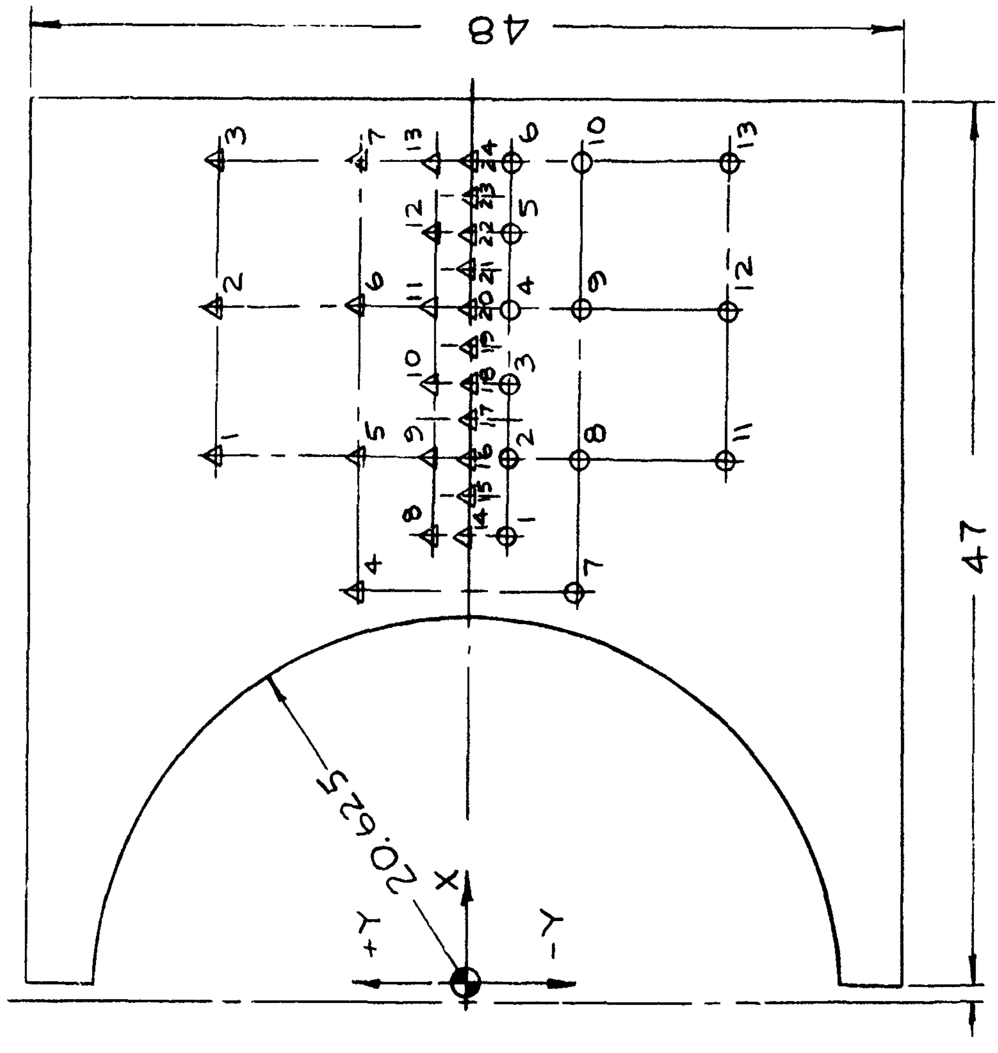

NOTE: Cutouts are for mounting models.
See table 3 for instrumentation locations.

FIGURE 4. Turntable Skin



**NOTE:** See table 4 for instrumentation locations

FIGURE 5. Forward Floor Skin




NOTE: See table 5 for instrumentation locations

FIGURE 6. Aft Floor Skin

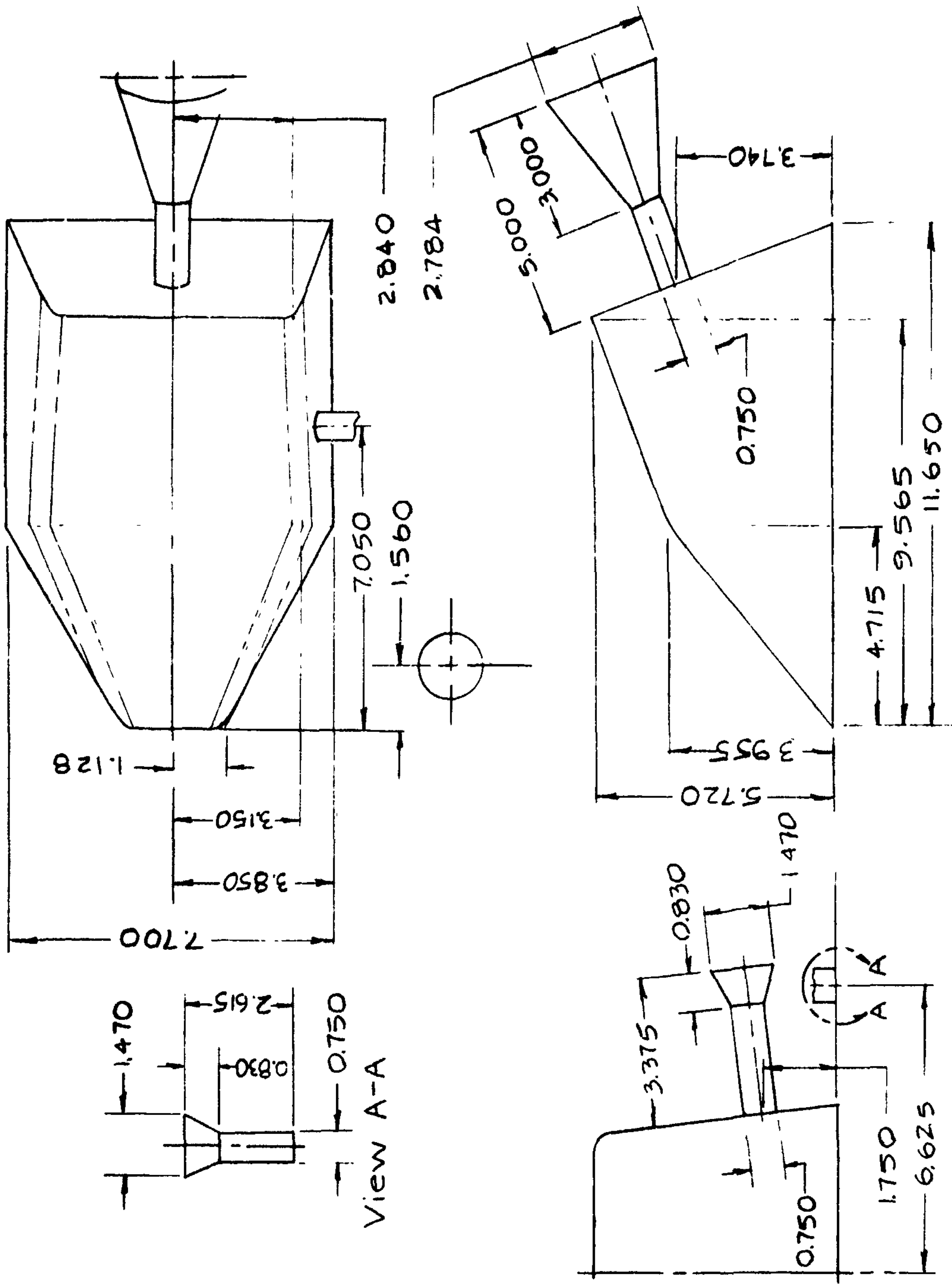



FIGURE 7. Thrustor Assembly Model Basic Dimensions

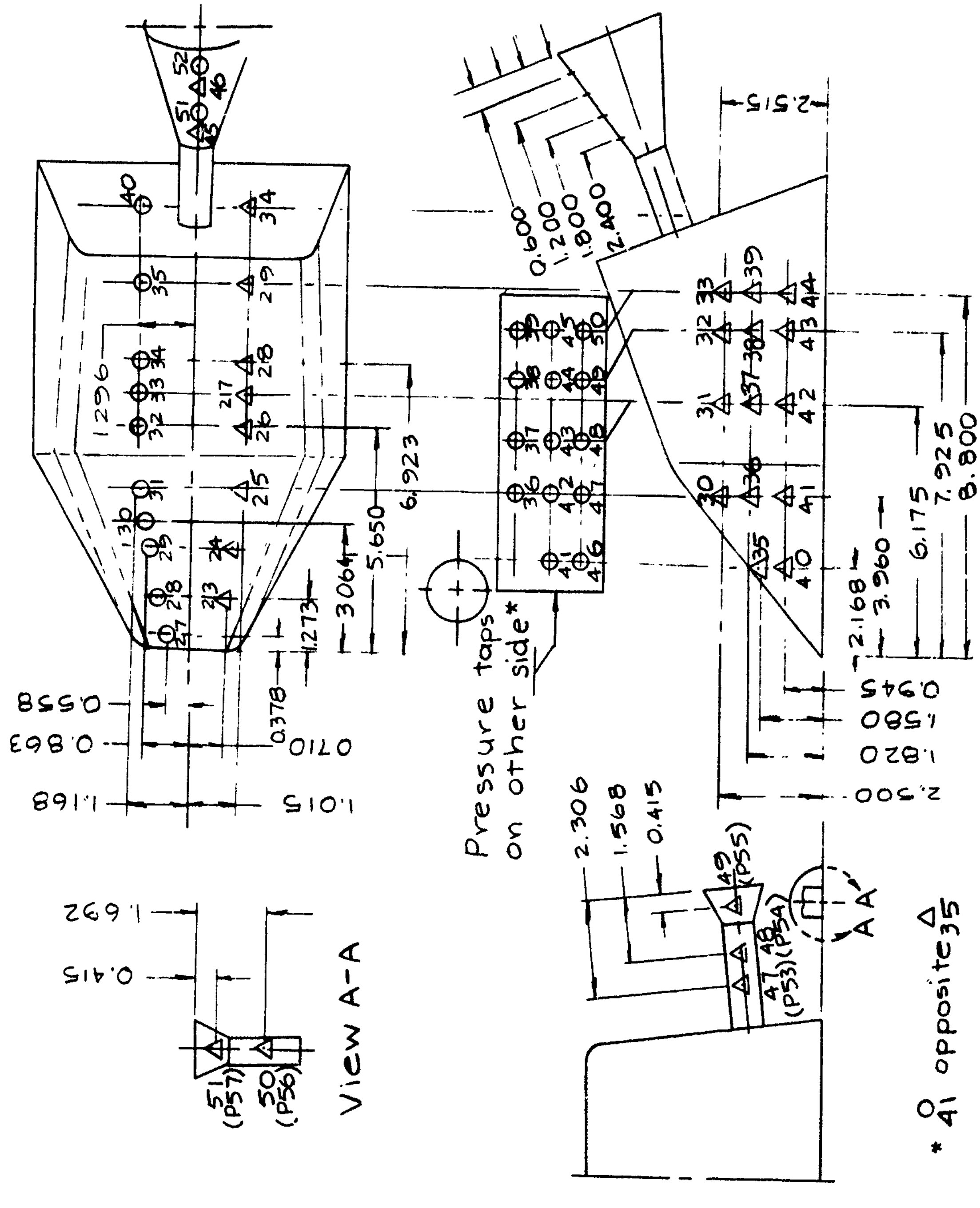



FIGURE 8. Thrustor Assembly Model Instrumentation Locations

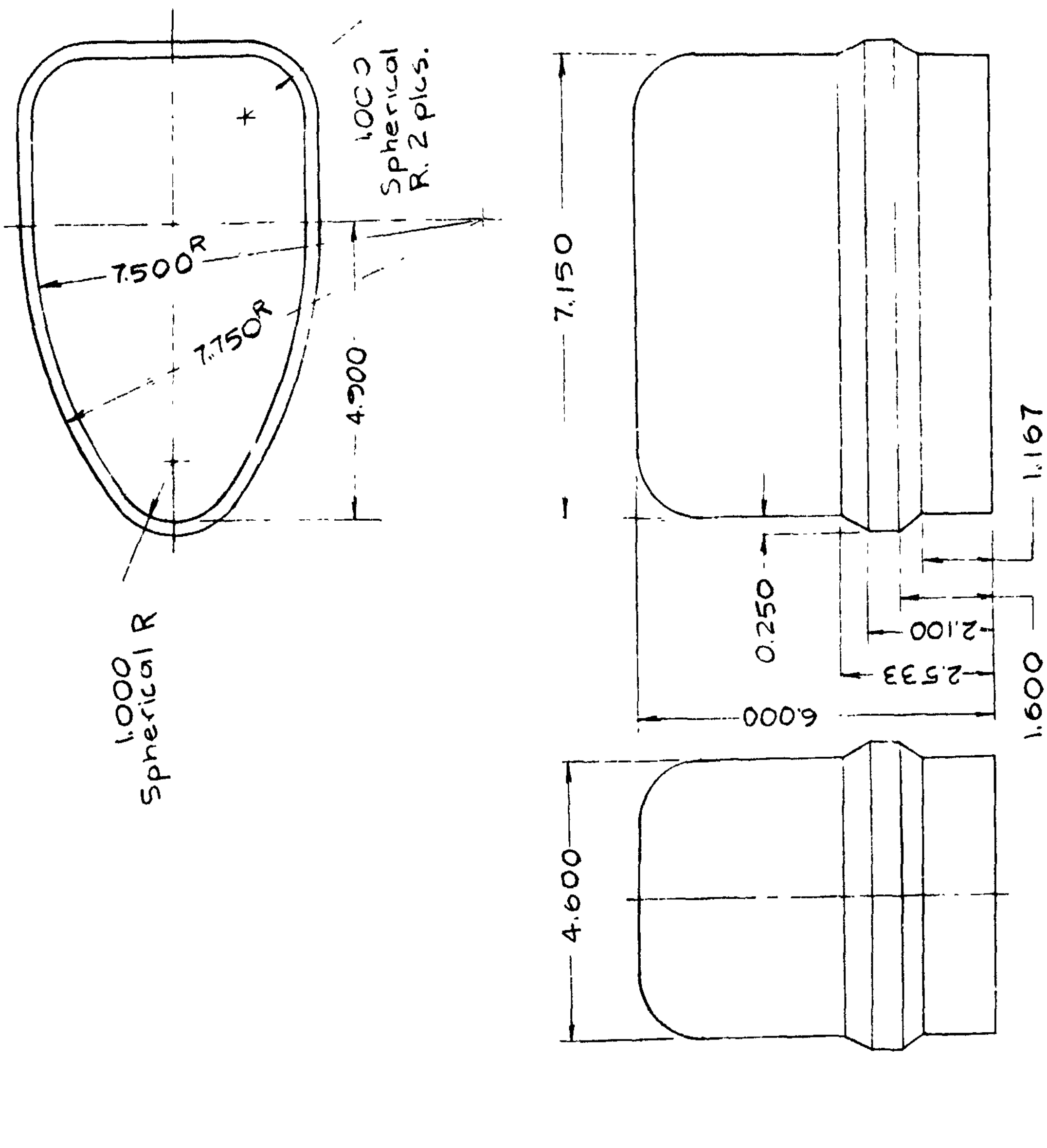



FIGURE 9. VVSA Model Basic Dimensions

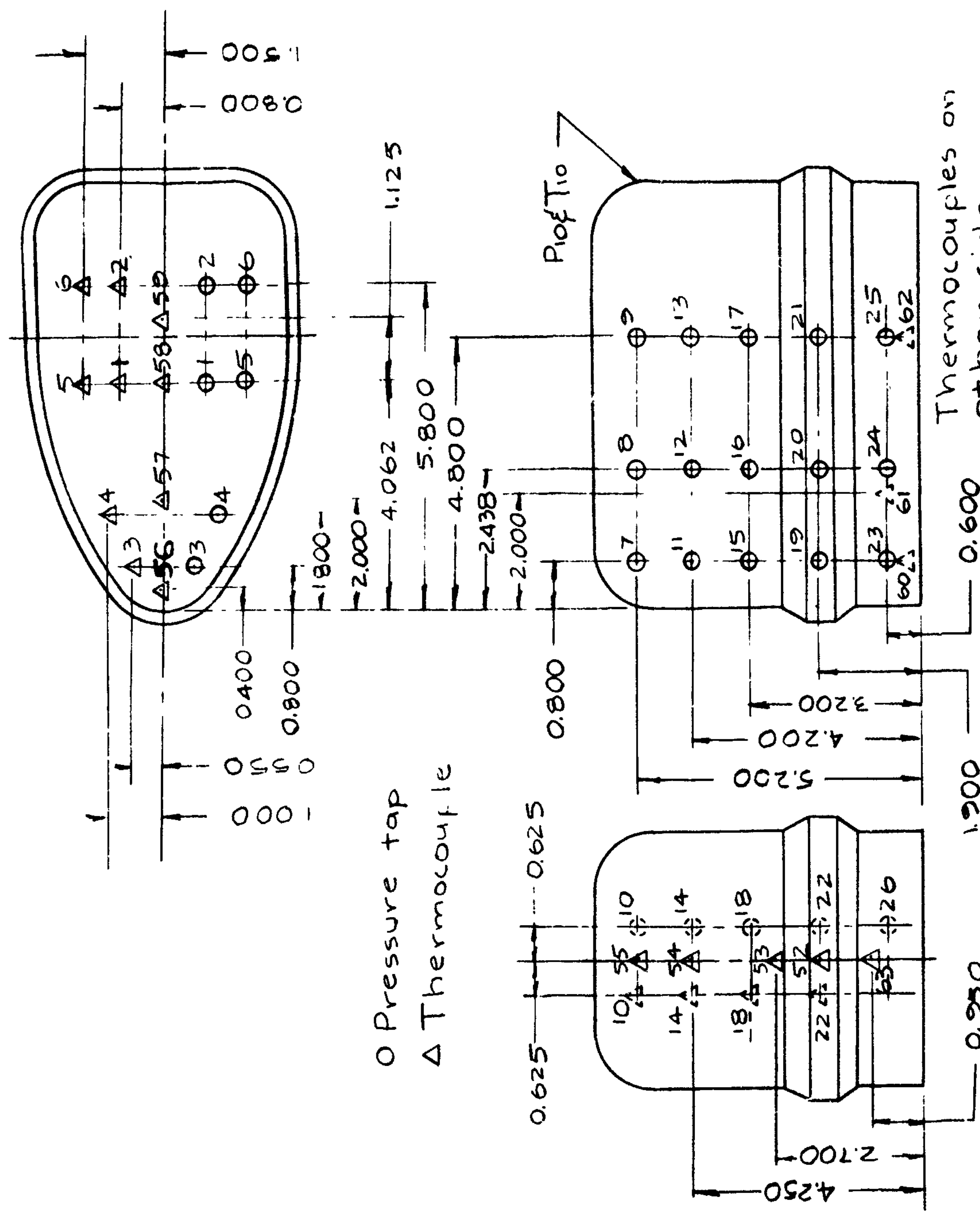



**FIGURE 10. VVSA Model Instrumentation Locations**

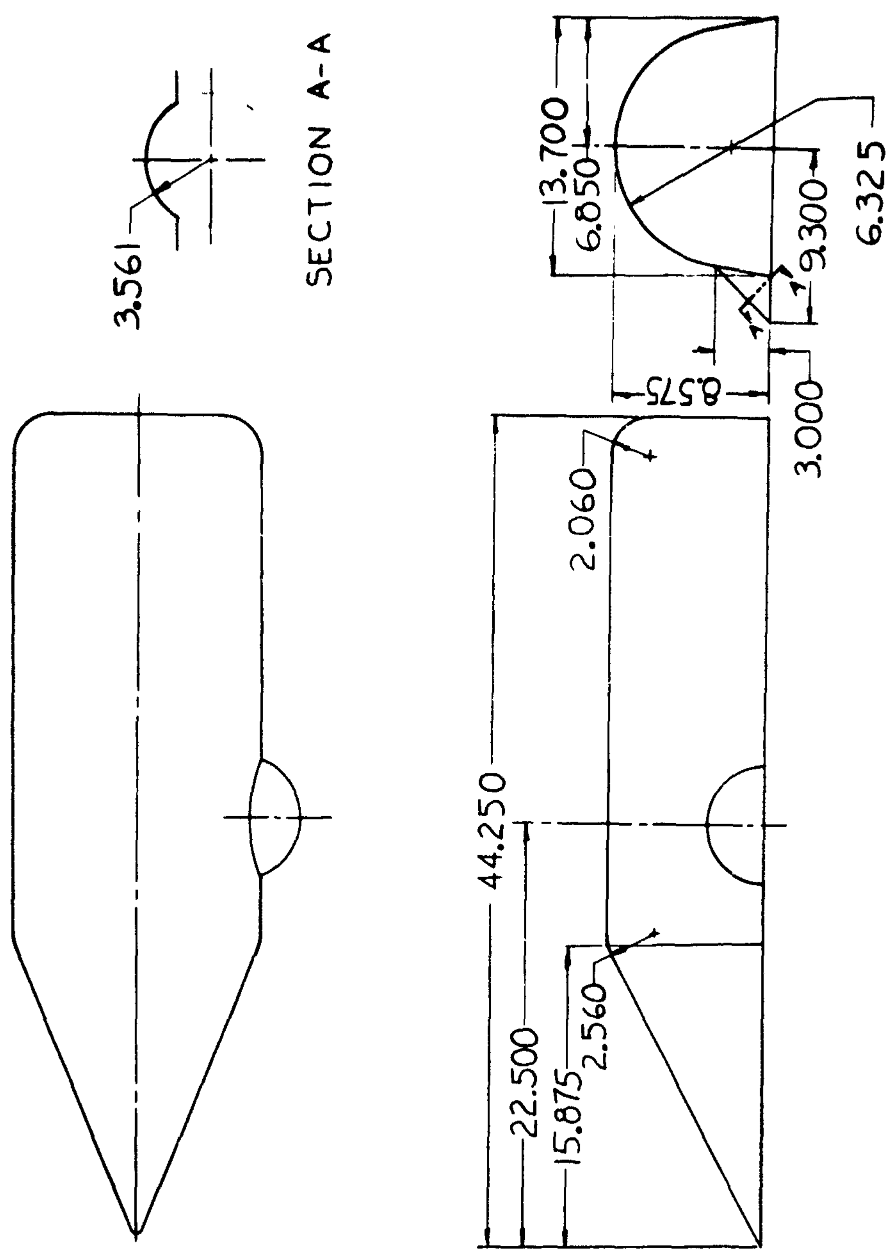



FIGURE 11. Asymmetric Model Basic Dimensions

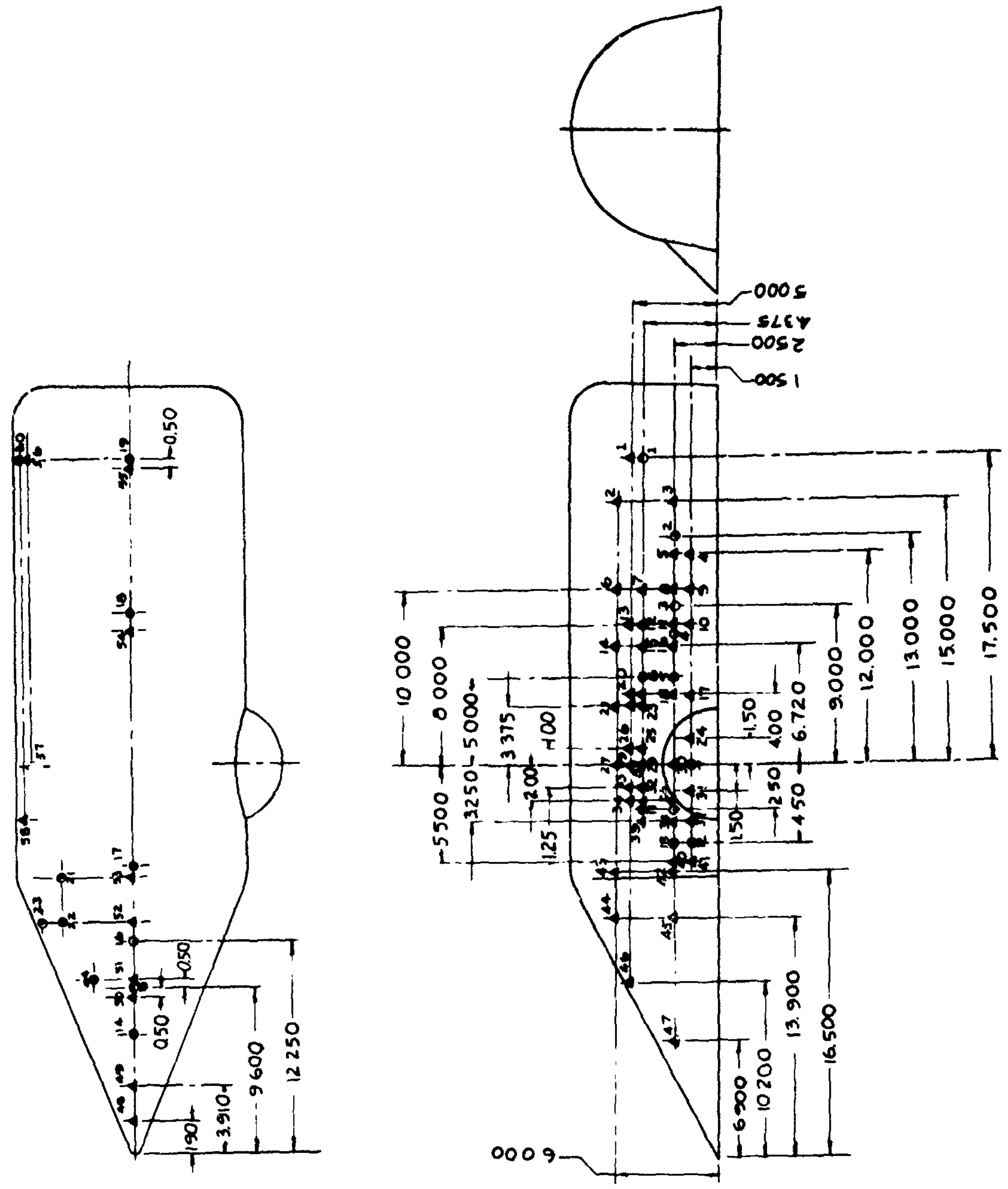


FIGURE 12. Asymmetric Model Instrumentation Locations

## APPENDIX I

## EQUATIONS AND DEFINITIONS OF SYMBOLS

### EQUATIONS

#### Heat Transfer Calculations

If it is assumed that there are no losses to the environment such that all heat into the model is stored in the skin, the heat transfer rate can be expressed as

$$\dot{q} = F_q \, wd \, C_p \frac{dT}{dt}$$

From the definition of heat transfer coefficient, and using $\dot{q}$ from the above equation,

$$h = \frac{\dot{q} \, F_h}{T_{aw} - T}$$

T is a temperature calculated at the midpoint of a quadratic determined from 21 consecutive thermocouple measurements.

Equations for some of the symbols used above:

$$F_q = \frac{\sin \beta}{\beta}$$

$$F_h = \frac{\tan \beta}{\beta}$$

$$\beta = \left( -1.5 + \sqrt{2.25 + 3 \lambda} \right)^{1/2}$$

$$\lambda = \frac{wd \; C_p}{T_{aw} - T_w} \frac{dT}{dt} \frac{d}{k}$$

$$T_{aw} = T \left( 1 + 0.2 \, (0.89) \, M^2 \right)$$

In addition to the above value of h, a theoretical value will be calculated from

$$h_o = 0.58\ C_f\ \rho_\infty\ U_\infty\ C_{P\infty}$$

$C_f$ is a local turbulent skin friction coefficient that will be calculated by the Spalding-Chi method, reference 5

This will probably be used as a reference to compare with test data and to calculate $h/h_o$ during the test (final data reductions would use the $h_o$ data collected during the test).

The parameters $F_h$, $F_q$, etc. are used to account for temperature gradients through the skin thickness. Development of these is provided in reference 3.

## Boundary Layer Survey Calculations

During the boundary layer survey, several freestream parameters will be calculated and printed out using $P_{T_\infty}$, $T_{T_\infty}$, and $M_\infty$ and NACA 1135 equations. In addition, the adiabatic wall temperature $T_{aw}$ will be calculated using the equation in the previous section.

For each of the probes in the boundary layer rake $P'_j$, $M_j$, $T_j$, $T_{Tj}$, $U_j$, $(\rho u)_j$, and $(\rho u^2)_j$ will be calculated. Equations to be used are as follows:

If the measured pressure at one probe is $P'_j$, $M_j$ can be calculated from the following:

$$\frac{P_w}{P_j} = \left(1 + \frac{M_j^2}{5}\right)^{-7/2} \qquad \text{if} \quad \frac{P_w}{P_j} \leq .5283$$

$$\frac{P'_j}{P_w} = \left(\frac{6M_j^2}{5}\right)^{7/2} \left(\frac{6}{7M_j^2 - 1}\right)^{5/2} \quad \text{if } \frac{Pw}{P_j} > .5283$$

The latter is the Rayleigh supersonic pitot formula for $\lambda = 1.4$.

The static temperature at each pressure probe is then

$$T_j = T_\infty \left\{ \frac{\left(\frac{T_{aw} - T_w}{T_\infty}\right)\frac{M_j}{M_\infty} + \sqrt{\left(\frac{T_{aw} - T_w}{T_\infty}\right)^2 \left(\frac{M_j}{M}\right)^2 + \frac{4\,T_w}{T_\infty}\left[1 + \frac{T_{aw}}{T_\infty} - \left(\frac{M_j}{M_\infty}\right)^2\right]}}{2\left[1 + \left(\frac{T_{aw}}{T_\infty}\right) - \left(\frac{M_j}{M_\infty}\right)^2\right]} \right\}^2$$

From this point, $T_{Tj}$, $\rho_j$, and $u_j$ can be determined from

$$u_j = M_j \sqrt{1.4\,(1716)\,T_j}$$

$$T_{Tj} = T_j \left(1 + \frac{M_j^2}{5}\right)$$

$$\rho_j = \frac{Pw}{1716\,T_j} \quad \text{slug/ft}^3 \text{ if Pw in lb/ft}^2\text{, T in }^\circ\text{R}$$

## Calculation of the Pressure Coefficient

During Phase III testing, the pressure coefficient for each orifice will be calculated according to

$$CP = \frac{P - P_\infty}{q_\infty}$$

where P is the orifice pressure.

## SYMBOLS AND DEFINITIONS

### English Alphabet Symbols

| Symbol | Description | Common Units |
|---|---|---|
| $B_i$ | Biot modulus | dimensionless |
| $C_p$ | Specific heat | Btu/lb-$^{\circ}$F |
| $C_{p_\infty}$ | Freestream specific heat of air | Btu/lb-$^{\circ}$F |
| CP | Pressure coefficient | dimensionless |
| $C_f$ | Local turbulent skin friction coefficient | dimensionless |
| d | Nickel skin thickness | ft |
| $F_o$ | Fourier modulus | dimensionless |
| $F_q$, $F_h$ | Correction terms for conduction effects through the skin | dimensionless |
| h | Heat transfer coefficient | Btu/sec ft$^2$ $^{\circ}$F |
| H | Protuberance height | in |
| k | Thermal conductivity | Btu/sec ft $^{\circ}$F |
| M | Mach number | dimensionless |

## SYMBOLS AND DEFINITIONS CONT'D

### English Alphabet Symbols

| Symbol | Description | Common Units |
|---|---|---|
| w | Density | $slug/ft^3$ |
| X | Along tunnel ℄ tunnel station | inches |
| Y | Transverse to tunnel | inches |
| Z | Height above floor | inches, ft |

### Greek Symbols

| Symbol | Description | Common Units |
|---|---|---|
| $\alpha$ | Thermal diffusivity | $ft^2/sec$ |
| $\beta$ | Yaw, positive to right looking upstream | degrees |
| $\delta$ | Boundary layer thickness | inches, ft. |
| $\lambda$, $\beta$ | Correction terms for conduction effects through nickel shell | dimensionless |
| $\rho$ | Density of air | $slug/ft^3$ |

### Subscripts

| Symbol | Description |
|---|---|
| j | Pertaining to local static condition (except for $P_j$ and $P'_j$) at a particular pressure tap on the boundary layer rake, j = 1, 2, 3... etc. |

## SYMBOLS AND DEFINITIONS CONT'D

### English Alphabet Symbols

| Symbol | Description | Common Units |
|---|---|---|
| N | $Z/\delta$; nondimensionalized height above tunnel floor | dimensionless |
| P | Pressure | psia |
| $P_j$ | A local stagnation pressure | psia |
| $P'_j$ | A local stagnation pressure behind a normal shock | psia |
| q | Dynamic pressure | psia |
| $\dot{q}$ | Heat transfer rate | Btu/sec $ft^2$ |
| Re/in | Unit Reynolds number | $in^{-1}$ |
| $Re_{x=0}$ | Total Reynolds number at metric plate leading edge, or tunnel station 106.563 | dimensionless |
| T | Temperature | $^oF$, $^oR$ |
| $T_{aw}$ | Adiabatic wall temperature | $^oF$, $^oR$ |
| t | Time | seconds |
| U | Freestream air velocity | ft/sec |
| u | Local air velocity | ft/sec |

## SYMBOLS AND DEFINITIONS CONT'D

### English Alphabet Symbols Cont'd

| Subscripts | Description |
|---|---|
| o | Pertaining to flat plate reference data |
| T | Stagnation condition |
| $T_\infty$ | Freestream stagnation condition |
| W | Used for floor or wall static pressure or temperature |
| $\infty$ | Freestream condition or freestream static condition |

## APPENDIX II

## STRENGTH ANALYSIS

### INTRODUCTION

A detailed, formal strength report is not required by the Douglas Aerophysics Laboratory because facility personnel have been intimately involved with design and development of the models. An internal memorandum (A2-260-ABC1-11 dated 2-14-68) published by the Structural Analysis Branch has satisfied laboratory requirements, so only a brief summary of the results will be presented.

### MOL Model M208 Strength Limitations

#### General

In the ensuing discussions, the terms "load factor" and "margin of safety" will have the following meanings:

The margin of safety is defined as

$$M.\ S. = \frac{f_a}{fL} - 1$$

Where M. S. is the margin of safety, $f_a$ is the material ultimate or yield strength, f is the actual stress, and L is the load factor.

The load factor is used as a multiplier of the actual stress as shown in the equation. Test facilities ordinarily require that a load factor of 5 be used in conjunction with the material ultimate strength during routine model design.

## APPENDIX II (CONT'D)

Comments concerning the strength of the important model components follow.

### Forward and Aft Metric Floor Sections

The strength of each nickel floor skin is considered when assembled with the respective insulator panel. For a load of 3 psi tending to lift up the floor, both the nickel and insulator show a large, positive margin of safety for a load factor of 5.

### Protuberance Models

Since the models are of very similar construction (i.e., the maximum unsupported area of nickel is a 3 inch square), the thruster only will be discussed, because it experiences the worst loads.

All panels of the module have a margin of safety of at least +0.47 (ultimate) for a load factor of 5. Mounting bolts for the module show a large, positive margin.

The mounting bolts are the weakest members in the nozzles. The bolts show a margin of safety of at least +0.3[illegible] (ultimate) based on a load factor of 5.

### Turntable

The turntable mount and the turntable tie-down bolts, the turntable base and its tie down bolts all will withstand 3 psi tending to lift the floor. The smallest margin is +0.22 (ultimate) for a load factor of 5.

The turntable skin is the weakest structural member of all model parts. The skin is point supported on a bolt spacing of [illegible].00 inches in a square pattern. For a 2.5 psi differential pressure on the skin that causes it to bear on the point supports, a margin of +0.23 (ultimate) with a load factor of 3 can be shown.

## APPENDIX II (CONT'D)

When a pressure of 3 psi tending to lift the floor is applied to the turntable skin, a margin of safety of +0.08 (ultimate) with a load factor of 1 can be shown. This margin will improve when the skin is precooled to -100°F, where the ultimate strength increases by 20%. When the protuberances are mounted, they will contribute to the strength.

### CONCLUSIONS

The strength of the turntable skin is marginal. Preliminary tests run at the Douglas Aerophysics Laboratory indicate the adverse pressure differential of 3 psi will occur during tunnel start, shoe retraction, and tunnel shutdown, and the duration will be one-half second.

Ordinarily, the Douglas Aerophysics Laboratory requires that models exhibit a positive margin of safety for a load factor of five on the material ultimate strength, or a load factor of three on the yield strength, whichever is smaller. However, acceptance of the MOL model is consistent with established laboratory policy. Section 5.6 of reference 2, which is concerned with model design criteria, states, "The recommended allowable stresses for testing without Schlieren viewing and with glass replaced by steel blanks may be appreciably higher and in many cases unrestricted." The tunnel will, in fact, be run in the above configuration so the model meets facility requirements.